

Resubmitted to the Astronomical Journal, Nov. 16, 2005

## 51 Eri and GJ 3305: A 10 – 15 Myr old binary star system at 30 parsecs

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### ABSTRACT

Following the suggestion of Zuckerman et al. (2001, ApJ, 562, L87), we consider the evidence that 51 Eri (spectral type F0) and GJ 3305 (M0), historically classified as unrelated main sequence stars in the solar neighborhood, are instead a wide physical binary system and members of the young  $\beta$  Pic moving group (BPMG). The BPMG is the nearest ( $d \lesssim 50$  pc) of several groups of young stars with ages around 10 Myr that are kinematically convergent with the Oph-Sco-Cen Association (OSCA), the nearest OB star association. Combining SAAO optical photometry, Hobby-Eberly Telescope high-resolution spectroscopy, *Chandra* X-ray data, and UCAC2 catalog kinematics, we confirm with high confidence that the system is indeed extremely young. GJ 3305 itself exhibits very strong magnetic activity but has rapidly depleted most of its lithium. The 51 Eri/GJ 3305 system is the westernmost known member of the OSCA, lying 110 pc from the main subgroups. The system is similar to the BPMG wide binary HD 172555/CD  $-64^{\circ}1208$  and the HD 104237 quintet, suggesting that dynamically fragile multiple systems can survive the turbulent environments of their natal giant molecular cloud complexes, while still being imparted high dispersion velocities. Nearby young systems such as these are excellent targets for evolved circumstellar disk and planetary studies, having stellar ages comparable to that of the late phases of planet formation.

*Subject headings:* binaries: visual – open clusters and associations: individual (Oph-Sco-Cen); planetary systems: formation – stars: individual (51 Eri, GJ 3305) – stars: pre-main sequence – X-rays: stars

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## 1. Introduction

### 1.1. Young stars near Earth are mostly OSCA outliers

Observations revealing the transition from gaseous circumstellar disks to protoplanets are not limited by the capabilities of telescopes but by the available samples of nearby young stars. Pre-main sequence (PMS) evolutionary models indicate that a 10 Myr old protoplanet with mass  $\geq 10 M_J$  should exhibit  $I < 20$  at a distance of 30 pc (Baraffe et al. 2002). The principal difficulties in finding stars with dissipating disks or protoplanets are that no active star forming regions lie within  $\sim 150$  pc and that older PMS stars drift far from their natal clouds where they are difficult to distinguish from the Galactic field population.

Most known nearby older PMS stars are kinematically linked to the populous Ophiuchus-Scorpius-Centaurus Association (OSCA) of PMS stars with its main concentrations at mean distances of 118 – 145 pc (Blaauw 1991; de Zeeuw et al. 1999). Ages range from 17 Myr in the Lower-Centaurus-Crux (LCC) subgroup (Mamajek et al. 2002) to  $< 1$  Myr in the Ophiuchus cluster where stars are still forming today. Several sparse populations distributed over the southern sky are kinematically convergent with the rapidly-moving OSCA and exhibit circumstellar disks, lithium excesses, or other indicators of stellar youth. These include the TW Hya Association (TWA),  $\beta$  Pic moving group (BPMG),  $\eta$  Cha cluster,  $\epsilon$  Cha group, and several ‘isolated’ Herbig AeBe stars with low mass companions. Their positions in the sky are shown in Figure 1 (a similar figure with proper motions vectors and references appears in Feigelson et al. 2003). These stars are distributed over a large region around the rich OSCA concentrations, likely propelled by supersonic motions of gaseous eddies in the OSCA’s turbulent giant molecular cloud (Feigelson 1996). It is quite likely that other stellar systems also lie away from the main OSCA subgroups. The BPMG in particular has members very close to the Sun. The circumstellar disk of its most massive member,  $\beta$  Pic ( $d = 19$  pc), has been subject to very intensive study (Lagrange et al. 2000) and a disk has recently been reported around the BPMG member AU Mic ( $d = 10$  pc; Kalas et al. 2004).

We discuss here two stars proposed by Zuckerman et al. (2001a) to be both a physical binary and nearby members of the  $\sim 12$  Myr old BPMG: the  $V = 5.2$  F0 star 51 Eri and the  $V = 10.6$  M0.5 star GJ 3305 separated by  $66''$ . This suggestion is in conflict with previous studies of these stars which have considered them to be unrelated older main sequence stars at  $d = 31$  pc and  $d = 15$  pc, respectively (§1.2). We present new X-ray and optical observations (§2), and consider in detail the kinematic, spectroscopic, photometric and magnetic activity properties of these stars (§3). We conclude that they indeed are outlying members of the OSCA. 51 Eri and GJ 3305 are thus among the nearest 10–15 Myr old stars and represent one

of the best nearby young stellar systems for study of planet formation. Their protoplanetary disks have largely dissipated and protoplanets might be detectable.

## 1.2. The misclassification of GJ 3305

The literature on 51 Eri and nearby associated stars has been confused. Figure 2a shows the neighborhood from the 2MASS *J*-band survey, and Table 1 lists the labeled stars. Many of these stars are missing from star catalogs due to saturation and diffracted light from the  $V = 5.2$  51 Eri, especially those based on all-sky Schmidt telescope photographic surveys. 51 Eri itself has a *Hipparcos* parallax measurement which, when combined with photometry and spectroscopy, confirms that it is a F0 star positioned on, or very near, the main sequence at a distance of  $29.8 \pm 0.8$  pc (for convenience, we call this 30 pc throughout this paper). From Burnham’s report in 1916, it was considered a double star with star 7 as its companion. But this is incorrect: kinematic measurements from the recent UCAC2 survey (Table 1; Zacharias et al. 2003) established that star 7 does not share the proper motions of 51 Eri and must be an unrelated star.

GJ 3305 has been classified, incorrectly in our view, as a disk dwarf with a photometric distance of  $\approx 15$  pc based on the assumption that the star resides on the main sequence. Propagation of this assumption has led to the inclusion of GJ 3305 in other catalogs and surveys of nearby stars, e.g. the Nearby Stars catalog<sup>1</sup> of Gliese & Jahreiss (1995) and the Palomar/MSU nearby star spectroscopic survey of Gizis et al. (2002). GJ 3305 is cataloged as a chromospherically-active flare star, presumably on account of its  $H\alpha$  emission, and more-recently of detection of strong X-ray variability by Fuhrmeister & Schmitt (2003). Their calculation of the total energy released during an X-ray flare detected during the *ROSAT* All-Sky Survey of  $3.4 \times 10^{34}$  erg is derived assuming a distance of 15.2 pc, with this value rising by a factor  $\approx 4$  if GJ 3305 instead resides at 30 pc as we argue in this paper. Across the characteristic timescale of the flare (we adopt 0.2 days) the luminosity of the flare was  $L_X \approx 8 \times 10^{30}$  erg s<sup>-1</sup>. For a spectral type of M0.5 and  $V = 10.6$  for GJ 3305 at 30 pc, and adopting the dwarf temperature and bolometric correction sequences of Kenyon & Hartmann (1995) as is appropriate for ‘older’ PMS stars (Mamajek et al. 2002; Lyo et al. 2004), we derive a stellar luminosity  $L_{bol} = 0.14 L_\odot$  and find the ratio of X-ray flux to bolometric flux to be  $\log L_X/L_{bol} \approx -1.8$  during the flare. Our *Chandra* observation indicates a lower quiescent level for GJ 3305 of  $\log L_X/L_{bol} \approx -3.5$ , a value similar to the ‘saturation’ level of

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<sup>1</sup>GJ 3305 does not appear in their published catalog but was added by the SIMBAD staff as a NN ‘new neighbour’ addition to the GJ catalog.

$\log L_X/L_{bol} \sim -3$  observed for magnetically-active late-type PMS stars.

## 2. Observations

### 2.1. Chandra X-Ray Observatory

A  $16' \times 16'$  region around 51 Eri was observed for 3.15 ks with the Advanced CCD Imaging Spectrometer (ACIS) detector on board the *Chandra X-Ray Observatory*. The instrument and detector are described by Weisskopf et al. (2002). This snapshot observation took place on 2003 November 20. Data analysis followed procedures described in Townsley et al. (2000), Townsley et al. (2003) and Getman et al. (2005) using the IDL- and CIAO-based script *acis\_extract* package<sup>2</sup>. One processing step, the removal of  $\pm 0.25''$  randomization in event location, was omitted due to the short exposure treated here. Figure 2b shows the central  $6' \times 6'$  of the resulting ACIS image after correction for charge transfer inefficiency and data selection steps. A spatial offset of  $0.7''$  was applied to align the sources associated with 51 Eri and GJ 3305 to the *Hipparcos* reference frame.

Thirty-one candidate X-ray sources were located using a wavelet-based detection algorithm (Freeman et al. 2002). Events for each source were extracted using *acis\_extract*. Here, events are extracted in a small region around each source containing 95% of the enclosed energy derived from the point spread function of the telescope at that position, and a local background is defined from a nearby source-free region. The extraction of GJ 3305 required a special annular region because the central pixels were subject to photon pileup, a saturation of the detector occurring when more than one photon arrives in a pixel during the 3.2 s between CCD readouts. We extracted 30% of the incident photons arriving between the 60% and 90% enclosed energy circles, and adjusted the effective area (CIAO's *arf* file) accordingly.

Most of these sources are extragalactic. Five were detected in a *ROSAT* pointed observation (WGACAT 0437.2-0210, 0437.3-0222, 0437.5-0236, 0437.6-0231 and 0437.8-0230) but have not been studied. Four have  $R \simeq 19 - 20$  counterparts on the Digitized Sky Survey and one is associated with the  $V \simeq 14.5$  S0 galaxy UGC 03105 at redshift  $z = 0.03$ . The remaining optical counterparts are too faint to appear in all-sky surveys. These sources are typical of the extragalactic population seen in *Chandra* images which often are active galactic nuclei with  $0.1 < z < 1$  (Brandt & Hasinger 2005).

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<sup>2</sup>Description and code for *acis\_extract* are available at [http://www.astro.psu.edu/xray/docs/TARA/ae\\_users\\_guide.html](http://www.astro.psu.edu/xray/docs/TARA/ae_users_guide.html).

Table 2 provides detailed results for the two stars of interest here. CXOU is the official designation of the *Chandra* X-ray sources. The positions have a precision of  $\pm 0.2''$ . *Extracted counts* gives the number of extracted counts in the total 0.5 – 8.0 keV *Chandra* band, while *Soft Counts* gives the subset of counts in the 0.5 – 2.0 keV band. Spectral analysis of 51 Eri and GJ 3305 is based on optically-thin plasma models with solar elemental abundances where the plasma energies  $kT$  are obtained by least-squares fit of the photon energy distribution using the *XSPEC* software package (Arnaud 1996). No interstellar absorption is seen in the spectra. The spectrum and best-fit model for GJ 3305 is shown in Figure 3. It requires a two-temperature plasma which is common in ACIS spectra of magnetically active late-type stars. Fluxes are found by integrating the best-fit spectrum over the 0.5 – 8 keV band, and luminosities are calculated assuming the *Hipparcos* distance to 51 Eri of 30 pc.

## 2.2. Hobby-Eberly Telescope spectroscopy

High-resolution spectra of 51 Eri and GJ 3305 were taken on three sequential nights, 2003 December 13 – 15 with the High Resolution Spectrograph (HRS; Tull 1998) on the 9.2-meter Hobby-Eberly Telescope (HET; Ramsey et al. 1998). The HRS uses an echelle mosaic with cross-dispersing gratings imaging onto a mosaic of two thinned  $2k \times 4k$  CCD detectors with  $15 \mu\text{m}$  pixels. The instrument lies in a stationary, climate-controlled room and is fiber-coupled to the primary focus of the telescope. The chosen  $600 \text{ gr mm}^{-1}$  grating with  $2''$  fibers gives resolving power  $R = 60,000$  over the interval  $\sim 5300 - 7250 \text{ \AA}$ . We obtained one 30 sec exposure of 51 Eri, and two 900 sec exposures of GJ 3305 each night, along with instrument calibration exposures.

The spectra were processed, extracted, and wavelength calibrated with standard IRAF routines. A difficulty arose because the instrument continuum calibration lamp for flat-fielding sometimes exhibits lithium Li I  $\lambda 6708 \text{ \AA}$  (sodium Na D) emission lines with 18% (12%) amplitude that coincide with stellar lines of interest. We replaced  $2 \text{ \AA}$  around each of these lines with a linear interpolation of the surrounding flat lamp spectrum;  $\approx 2\%$  systematic residual structure is expected from this procedure. For the GJ 3305 spectra, background spectra from two fibers pointed at blank sky were subtracted and cosmic rays were rejected. These steps were unnecessary for 51 Eri owing to the brightness and brevity of the exposures. Spectra from the three nights were combined and the continua of the wavelength-calibrated star spectra were removed. No radial velocity correction or calibration was made. No night-to-night variation in any spectral feature was seen.

Figure 4 shows the resulting spectra around the Na D,  $H\alpha$  and Li I  $\lambda 6708 \text{ \AA}$  lines. The signal-to-noise ratio at  $H\alpha$  and Li I  $\lambda 6708 \text{ \AA}$  is  $S/N = 230:1$  for GJ 3305 and  $180:1$  for 51

Eri. The strength of the lithium absorption line in GJ 3305 is of greatest interest in our discussion below. Figure 4c shows the spectra with a relatively low global continuum fit which gives a Li I  $\lambda 6708\text{\AA}$  equivalent width  $EW = 0.09\text{ \AA}$ . A continuum fit that passes near the peaks of local fluctuations, which takes into account our high  $S/N$  and the likely presence of uncatalogued absorption lines, gives  $EW = 0.14\text{ \AA}$ . (Jeffries et al. 2003 discuss the sensitivities of reported lithium line strengths to the choice of continuum levels.) A faint absorption line with  $EW = 0.03\text{ \AA}$  appears in the 51 Eri spectrum; we believe this is the residual from the interpolated continuum lamp calibration. The true GJ 3305 line strength may thus be  $0.03\text{ \AA}$  lower than measured here. Altogether, we adopt  $EW = 0.12 \pm 0.03$  for the Li I  $\lambda 6708\text{\AA}$  line of GJ 3305.

The weak  $H\alpha$  profile of GJ 3305 with roughly  $1\text{ \AA}$   $EW$  and little variability over 3 nights of observation is commensurate with GJ 3305 being a weakly-active, non-accreting PMS star. It has a spectroscopic analog in the several-Myr younger star RECX 10 in the  $\eta$  Cha cluster, with a spectral type of M0.3 determined from precise spectrophotometric study (Lyo et al. 2004). Both stars have weak, narrow  $H\alpha$  profiles of  $1\text{ \AA}$   $EW$  and velocity width (measured at the 10% height of the emission line profile above the surrounding continuum)  $v_{10} = 110\text{ km s}^{-1}$  indicative of a line of chromospheric origin, with no evidence for wing-broadening that might indicate on-going low levels of disk accretion (Lawson et al. 2004). At echelle resolution, the  $H\alpha$  profiles of both stars show weak self-absorption signatures.

In the spectral regions of interest here, the principal difference between GJ 3305 and RECX 10 is the strength of the Li I  $\lambda 6708\text{\AA}$  line;  $EW = 0.12\text{ \AA}$  for GJ 3305 (see the discussion above) and  $EW = 0.6\text{ \AA}$  for RECX 10 (measured from unpublished echelle spectra; Mamajek et al. 1999 had earlier obtained a similar result of  $EW = 0.5\text{ \AA}$  from medium-resolution spectra). Our measurement of low lithium  $EW$  in GJ 3305 reinforces the evidence that significant lithium depletion can be present in 10 – 15 Myr stars (§6). Zuckerman et al. (2001a) used lithium measurements as evidence that the BPMG has an age intermediate between that of the TWA ( $\sim 10$  Myr) and Tucana-Horologium ( $\sim 30$  Myr) group stars. Adding our lithium measurement for GJ 3305 to those for 3 late-type BPMG candidate members with spectral types ranging from K0 to M1 measured by Zuckerman et al. (2001a, see their Table 2) gives an average lithium  $EW = 0.26\text{ \AA}$ . GJ 3305 has the lowest  $EW$  by a factor of  $\approx 2$  compared to the other three stars, and thus signals that depletion has been unusually efficient in this star. This average  $EW$  for BPMG candidate members compares to average values of  $\approx 0.5\text{ \AA}$  for late-type members of both the  $\sim 10$  Myr-old TWA (Webb et al. 1999) and  $\eta$  Cha star cluster (Mamajek et al. 1999).

### 2.3. South African Astronomical Observatory photometry

We have obtained a tentative measure of the rotation period of GJ 3305 by searching for optical photometric variations that are modulated by the periodic rotation of starspots. A series of observations was made in the *BVRI* photometric bands over 6 consecutive nights from 2004 December 8 – 13 with the 1-m telescope and a  $1\text{k} \times 1\text{k}$  CCD detector at the South African Astronomical Observatory (SAAO). Four sets of observations were obtained on most nights, to reduce the 1-day aliasing effects that can result from observations being made at a single observing site. The observations and analysis of the photometry follows that described by Lawson et al. (2001). In summary, differential measurements of the suspected variable star are produced by comparison with other stars in the CCD field that are assumed to be constant, and the resulting differential light curve is then subject to Fourier analysis. Unfortunately GJ 3305 resides in a sparse field towards the Galactic anti-center ( $\ell, b = 199^\circ, -31^\circ$ ) resulting in few usable comparison stars within a radius of several arcmin. With exposure times optimized for GJ 3305, only in *B*-band were there nearby field stars of comparable brightness to GJ 3305; in the other bands the usable comparison stars were a few magnitudes fainter than GJ 3305 resulting in unacceptable noise in the differential observations. We therefore describe only the analysis of our *B*-band observations here.

The *B*-band light curve shows variations of low amplitude over the duration of the observations. Fourier analysis of the light curve recovered a periodicity at  $f = 0.164\text{ d}^{-1}$ , or  $P = 6.1$  days (Figure 5). The recovered period is comparable to the length of the observing run, and so we treat the result with caution, but the data when phased to a period of  $\approx 6$  days have less scatter than when they are phased to substantially different periods. We therefore tentatively adopt a period of  $P = 6.0 \pm 0.5$  days for GJ 3305, and await the acquisition of photometry obtained across a longer timeline to confirm and improve this result. In the upper panel of Figure 5 we show our *B*-band photometry phased on a periodicity of  $f = 0.164\text{ d}^{-1}$ . In the lower panel we show the amplitude spectra of the photometry (bold line), and that following pre-whitening of the dataset with the identified periodicity (thin line), across a frequency range of  $0 - 2\text{ d}^{-1}$ . The collapse of the  $f = 0.164\text{ d}^{-1}$  periodicity and its associated  $(1 - f)\text{ d}^{-1}$  and  $(1 + f)\text{ d}^{-1}$  aliases in the pre-whitened spectrum suggests the period of GJ 3305 is not far-removed from  $P = 6$  days. For a sine wave amplitude of  $0.015\text{ mag}$ , and adopting a noise level of  $0.003\text{ mag}$  over the  $0 - 2\text{ d}^{-1}$  frequency interval, the periodicity has a S/N ratio of 5. At higher frequencies both the original and pre-whitened spectra show noise at a level of  $\approx 0.05\text{ mag}$ , indicating that the variations seen within an individual night of data are the result of random photometric noise and not due to the presence of high frequency periodicities.

### 3. Evolutionary status of 51 Eri and GJ 3305

In this section we reevaluate the evolutionary state of these two stars based on various lines of argument. It is worthwhile to recall that it is very difficult to determine the age of isolated AF-type stars on or near the main sequence from their spectral and photometric properties due to the convergence of isochrones in the HI diagram. We note especially the extended debate concerning the age of the A3 star  $\beta$  Pic. Once considered to be a post-main sequence star with age  $t \simeq 200$  Myr or a main sequence star with age  $t \simeq 100$  Myr, its kinematical association with PMS stars and the OSCA strongly argue for an age around 10 – 15 Myr (Barrado y Navascués et al. 1999; Mamajek & Feigelson 2001; Zuckerman et al. 2001a; Ortega et al. 2002, 2004). We synthesize several lines of evidence that together strongly argue that 51 Eri and GJ 3305 are also OSCA outliers with ages 10 – 15 Myr.

#### 3.1. Astrometry and kinematics

The UCAC2 proper motion of GJ 3305  $(\mu_\alpha, \mu_\delta) = (46.1, -64.8)$  mas yr<sup>-1</sup> is nearly identical to the proper motion of  $(\mu_\alpha, \mu_\delta) = (43.3, -64.3)$  mas yr<sup>-1</sup> found by *Hipparcos* for 51 Eri itself. None of the other  $\approx 6000$  UCAC2 stars within an area of 10 deg<sup>2</sup> centered on the position of 51 Eri have a proper motion within 10 mas yr<sup>-1</sup> of that of 51 Eri. We have already established that the 51 Eri motion is convergent with the OSCA 10 – 15 Myr ago; see Figure 1. The radial velocity of 51 Eri is  $21 \pm 2$  km s<sup>-1</sup> (Kharchenko et al. 2004). Although we did not calibrate our HET spectra against radial velocity standards, differential velocity measurements of spectral features in 51 Eri and GJ 3305 suggests both stars share the same radial velocity to within 2 km s<sup>-1</sup>.

#### 3.2. Magnetic activity

GJ 3305 has an X-ray to bolometric luminosity ratio  $\log L_X/L_{bol} = -3.5$  which is near the saturation level of  $\log L_X/L_{bol} \sim -3$  for late-type magnetically active PMS stars. This is far above the range of  $\log L_X/L_{bol} = -5.2 \pm 0.5$  seen in old disk early-M type stars (Fleming et al. 1995). A faint X-ray source with  $L_X = 1.4 \times 10^{28}$  erg s<sup>-1</sup> and a soft spectrum coincides with the F0 primary, 51 Eri. At 30 pc distance, this yields a low value of  $\log L_X/L_{bol} = -6.2$  as is expected from the quiescent coronal gas in the atmosphere of an F0 star.

This high level of X-ray emission is a strong indicator for stellar youth. We compare  $\log L_X/L_{bol}$  of GJ 3305 with stars in other young stellar clusters and associations in Figure

$6a^3$ . Due to mass-dependencies in pre-main sequence X-ray emission (Preibisch et al. 2005), we limit the comparison to stars in a limited spectral range. The saturated X-ray level implies an age  $\lesssim 100$  Myr.

### 3.3. HR diagram

In Figure 7 we compare the location of 51 Eri and GJ 3305 in the HR diagram to the predictions of the PMS evolutionary tracks of Siess et al. (2000). The error bars indicate the effect of a nominal 0.5 sub-type uncertainty in the spectral types of the two stars; F0 for 51 Eri and M0.5 for GJ 3305. The resulting range in the stellar luminosities caused by the adoption of the 0.5 sub-type uncertainty is encompassed by the plotted size of the points in Figure 7. 51 Eri may lie slightly elevated above the ZAMS of Siess et al. (2000), although only marginally-so owing to the adopted uncertainty and the coarseness of the grid in the temperature range appropriate for F-type stars. At 30 pc distance, GJ 3305 is clearly PMS with an inferred age of  $13_{-3}^{+4}$  Myr, consistent with the age estimate of  $12_{-4}^{+8}$  Myr given for the BPMG by Zuckerman et al. (2001a) and the 17 Myr age given for the rich LCC OSCA subgroup by Mamajek et al. (2002). From comparison with the models of Siess et al. (2000) we obtain  $M = 1.6 M_{\odot}$  for 51 Eri, and  $M = 0.5 M_{\odot}$  for GJ 3305.

### 3.4. Multiplicity and dynamical state

If we assume that the physical separation of 51 Eri/GJ 3305 is close to the projected separation of  $66''$ , or  $\simeq 2000$  AU at  $d = 30$  pc, and that the orbit is circular, then the binary orbital period is  $\simeq 60,000$  yr and an orbital velocity of GJ 3305 is  $\approx 0.7$  km s $^{-1}$ . This represents a very fragile system; any dynamical perturbation of order 1 km s $^{-1}$  during the

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<sup>3</sup>The symbols and sources for Figure 6 are obtained as follows. GJ 3305 (this paper) and CD  $-64^{\circ}1208$  (Zuckerman et al. 2001a) are shown as large open stars. For the X-ray data: young PMS stars are from the Orion Nebula Cluster (Getman et al. 2005, circles) and the Taurus-Auriga cloud (Neuhäuser et al. 1995),  $\sim 10$  Myr PMS stars are from the TW Hya Association (Webb et al. 1999, squares),  $\sim 30$  Myr stars are from NGC 2547 (Jeffries & Tolley 1998),  $\sim 100$  Myr stars are from the Pleiades (Stauffer et al. 1994), and  $> 1$  Gyr old stars are from the Gliese catalogue (Schmitt & Liefke 2004). For the lithium data: young PMS stars are from the Taurus-Auriga clouds (Martín et al. 1994, circles) and  $\sigma$  Orionis cluster (Zapatero Osorio et al. 2002, squares), old PMS stars are from the OSCA Upper Scorpius subgroup (Preibisch et al. 1998, circles) and the TW Hya Association (Webb et al. 1999; Sterzik et al. 1999; Zuckerman et al. 2001b, squares), and  $\sim 30$  Myr stars from the IC 2602 and IC 2391 clusters (Randich et al. 2001, circles) and NGC 2547 cluster (Jeffries et al. 2003, squares).

last 10 – 15 Myr would have been sufficient to disrupt the binary, yet the binary system has completed  $\sim 200$  orbital periods. This is reminiscent of a similar multiple system: the four low-mass PMS stars with 500 – 1500 AU orbits around the 3 – 5 Myr intermediate-mass Herbig Ae star HD 104237 which is also kinematically linked to the OSCA (Feigelson et al. 2003). Systems such as 51 Eri and HD 104237 must have originated in a dynamically quiescent star formation environment. Dynamical simulations of stellar clusters by Kroupa (1998) indicates that wide binaries with total mass around  $2 M_{\odot}$  and mass ratio around 3:1, as in 51 Eri/GJ 3305, can survive if the initial star density is not too high.

### 3.5. Rotational velocities

The  $v \sin i$  projected rotational velocity of 51 Eri was measured to be  $71.8 \pm 3.6 \text{ km s}^{-1}$  by Reiners & Schmitt (2003), with indications from suspected asymmetries and variations in the line profiles that the star was spotted. 51 Eri is listed as a candidate *Hipparcos* variable star by Koen & Eyer (2002), with a period determined by Fourier analysis of the *Hipparcos* photometry of  $P = 0.65 \text{ d}$ , with a fitted sine wave amplitude of 0.005 mag. For a F0 dwarf on or near the main-sequence with characteristic mass and radius of  $M \approx 1.5 M_{\odot}$  and  $R \approx 1.5 R_{\odot}$ , the  $v \sin i$  velocity and proposed period of the star can be reconciled if 51 Eri is being observed at a moderate inclination angle of  $i \sim 45^{\circ}$ .

There is no literature value for the projected rotational velocity for GJ 3305; however our HET spectra for GJ 3305 show line profiles for absorption lines near  $H\alpha$  of width exceeding the expected instrumental broadening due to the HRS. From the measured FWHM of the profiles we estimate the contribution from all sources of line broadening to be  $v \sim 10 \text{ km s}^{-1}$ . Thus  $v \sin i < 10 \text{ km s}^{-1}$  and for a young  $R \approx 0.7 R_{\odot}$  early-M star the inferred rotation period is  $P > 4 \sin i$  days, consistent with our tentative measured rotation period of  $P = 6.1$  days; see §2.3. We have not attempted a line profile deconvolution that would allow us to accurately determine the projected rotational velocity for the star.

## 4. Origin of the 51 Eri and GJ 3305 system

There is little doubt that 51 Eri and its companion constitute a physical binary. Not one of several thousand UCAC2 stars in the immediate vicinity share the unusually large proper motions seen in these two stars.

We conclude that both the  $1.6 M_{\odot}$  51 Eri and its X-ray selected companion  $0.5 M_{\odot}$  companion are  $\simeq 10 \text{ Myr}$  outlying members of the OSCA. They are now seen at an angular

distance of  $\simeq 100^\circ$ , and a physical distance of  $\simeq 110$  pc, from the center of the nearest (LCC) rich concentration of OSCA stars. This implies that the 51 Eri system was formed from molecular gas with a velocity vector displaced  $\sim 9 \text{ km s}^{-1}$  from that of the rich OSCA concentrations. This is consistent with dispersions seen over large scales in giant molecular cloud complexes which are attributed to turbulence (Feigelson 1996).

OSCA outliers include a number of PMS stars with rapid gas accretion from infrared-bright (*IRAS*-detected) circumstellar disks. These include TW Hya and Hen 3-600A in the TWA (Muzerolle et al. 2000), ECHAJ 0843.3–7905 and RECX 11 in the  $\eta$  Cha cluster (Lawson et al. 2004), and the several Herbig Ae/Be stars noted in Figure 1.  $\beta$  Pic has a prominent reflection disk and is accreting cometary-sized bodies (Lagrange et al. 2000). In contrast, both 51 Eri and GJ 3305 appear to lack prominent disks. 51 Eri displays a  $(V - K)$  color of 0.68, consistent with its F0 spectral type. However, the star may have a small  $(K - [12])$  excess of  $0.2 \pm 0.1$  when compared to dwarf colors assembled by Kenyon & Hartmann (1995), which may indicate the presence of a weak disk. GJ 3305 has 2MASS *JHK* colors consistent with its listed spectral type of M0.5; however it has  $(V - [2MASS])$  colors closer to that of an M2 dwarf which may indicate the presence of a weak disk, or a minor mis-classification of its spectral type. We note that GJ 3305 has no known late-M companion; McCarthy & Zuckerman (2004) included GJ 3305 in an unsuccessful search to detect brown dwarfs orbiting at  $a = 75 - 300$  AU around a hundred nearby G-, K-, and M-type stars.

Sensitive near-infrared coronagraphic imagery and far-infrared photometry with the *Spitzer Space Observatory* may detect faint, evolved disks around one or both stars. Perhaps most exciting is the possibility that, with disks that have largely dissipated, protoplanets might be present around these stars. For example, making use of the sub-stellar models of Baraffe et al. (2002), a  $5 M_J$  planet in a circular face-on orbit with  $a = 30$  AU should appear as a  $K = 15.4$  source at a separation of  $1''$  from the star. For such a planet surrounding GJ 3305,  $\Delta K = 9$  mag; this is a demanding but not insurmountable challenge using existing technologies.

## 5. HD 172555/CD -64°1208 and other similar wide binary systems

While it may seem at first unlikely that a weakly bound binary can survive the turbulent environment of the OSCA giant molecular cloud, a considerable fraction of the identified BPMG members are similar. Visual multiple systems in the list of Zuckerman et al. (2001a) include 51 Eri/GJ 3305 (F0+M0.5 with projected separation 2200 AU), HD 155555ABC (G5+K0+M4.5, 400 AU), HD 172555/CD -64°1208 (A7+K7, 2000 AU), HR

7329AB (A0+M7, 200 AU), and HD 199143AB/BD -17°6128AB (primaries F8+K7, 15000 AU Kaisler et al. 2004).

Of these, the HD 172555/CD -64°1208 system is remarkably similar to 51 Eri/GJ 3305. HD 172555 = HR 7012 is a mid-A star lying far to the southeast of the main OSCA concentrations in the sky (Figure 1). Its spectral type has been variously classified as A2 to A7; Houk & Cowley (1975) give A5 IV–V while Gray & Garrison (1989) give A6 IV based on spectral line shapes. With a *Hipparcos* parallactic distance of  $29.2 \pm 0.6$  pc, an enormous proper motion oriented southward  $(\mu_\alpha, \mu_\delta) = (32.7, -148.7)$  mas yr<sup>-1</sup>, and a roughly measured radial velocity of  $+2 \pm 5$  km s<sup>-1</sup>, its closest approach to the OSCA was 11 Myr ago when it lay  $\sim 29$  pc from the Upper Centaurus Lupus (UCL) subgroup.

This intermediate-mass star has a comoving companion CD -64°1208 with spectral type M0,  $V = 10.4$  and  $K = 6.1$ . Whereas the older literature did not indicate a relationship between 51 Eri and GJ 3305, various proper motion surveys since Fallon (1983) showed that HD 172555 and CD -64°1208 are approximately comoving. The most accurate proper motion for the M0 star is from the UCAC2 catalog with  $(\mu_\alpha, \mu_\delta) = (30 \pm 14, -153 \pm 14)$  mas yr<sup>-1</sup> which is consistent with the A star. Only 0.04% of stars within  $\approx 2.5^\circ$  of HD 172555 have UCAC2 motions within  $\pm 20$  mas yr<sup>-1</sup> of its value.

A spectrum of CD -64°1208 reported by Zuckerman et al. (2001a, footnote to Table 1) shows H $\alpha$  in emission with  $EW(\text{H}\alpha) = 2.2$  Å and strong lithium in absorption with  $EW(\text{Li I } \lambda 6708) = 0.58$  Å. Its X-ray emission is very strong, about 1 cts s<sup>-1</sup> in ROSAT proportional counter observations (Simon & Drake 1993) with a soft X-ray spectrum, strong extreme-ultraviolet emission and possibly the source of a soft X-ray flare seen with the early non-imaging *Ginga* satellite (Kreysing et al. 1995; Thomas et al. 1998; Forster et al. 1999). We have obtained a brief *Chandra* snapshot of the region with the ACIS detector (ObsID = 5180, 2004 Mar 10; not displayed here). The mid-A primary is not seen with a limit  $\log L_x < 26.9$  erg s<sup>-1</sup> (0.5 – 8 keV) but the M0 secondary is detected with  $\simeq 0.2$  ct s<sup>-1</sup>. The corresponding luminosity at  $d = 29$  pc is  $\log L_x \simeq 29.5$  erg s<sup>-1</sup>. Similar to GJ 3305, this is near the top of the X-ray luminosity function for M dwarfs and indicates a very young age.

These two binary systems, 51 Eri/GJ 3305 and HD 172555/CD -64°1208, share many properties: a (coincidental) distance of 30 pc from the Sun, a factor of 3 – 4 mass ratio, a projected separation of 2000 AU, very strong X-ray emission in the lower mass star, compatible very-high velocity proper motions pointed towards an origin in the OSCA, and a location of the lower mass star above the main sequence assuming it is codistant with the higher mass star. They differ only in their distant locations from each other and the OSCA concentrations in the sky, and in the strength of the lithium line which is 5 times stronger in CD -64°1208 than GJ 3305. Masciadri et al. (2005) have conducted a high-resolution

near-infrared imaging search for planetary companions around CD  $-64^{\circ}1208$ ; no gaseous companion with mass  $> 5 M_J$  was found with orbital radius  $> 15$  AU.

## 6. Discussion

The evidence is clear that 51 Eri and GJ 3305 together are a young, wide binary system at  $d = 30$  pc. The distance to 51 Eri is directly measured by parallax, and has a high-velocity space motion that is convergent with the OSCA. GJ 3305 shares its unusual proper motion, and is thus very unlikely ( $P < 0.0002$ ) to be an unrelated star. Assuming a 30 pc distance, GJ 3305 lies on the  $\simeq 13$  Myr isochrone on the H-R diagram. It exhibits moderately strong chromospheric emission and extreme X-ray emission with powerful X-ray flares. Its photometric variability is probably due to starspots modulated with a 6-day period. Its spectrum shows an abundance of lithium intermediate between the primordial levels seen in young T Tauri stars and the fully depleted main sequence stars. From this confluence of evidence, we conclude with confidence that both 51 Eri and GJ 3305 are OSCA outliers with ages around 10 – 15 Myr similar to the UCL and LCC OSCA subgroups.

The main anomaly is the relatively weak Li I  $\lambda 6708$  line compared to other OSCA stars (Figure 6b). However, it is well-known that ZAMS stars exhibit a wide range of lithium levels and there is growing evidence that a small fraction of M stars undergo rapid lithium depletion while on their pre-main sequence tracks. In addition to the BPMG stars discussed in §2.2, Song et al. (2002) report a M4+M4.5 BPMG binary where the two components show an order of magnitude difference in lithium line strength ( $EW = 300$  mÅ and  $EW < 30$  mÅ). A spectroscopic survey for lithium in  $\sim 10$  Myr Orion Nebula Cluster stars shows a few lithium-depleted stars contemporaneous with the dominant population of undepleted stars (Palla et al. 2005). Conversely, a survey of the 35 Myr NGC 2547 cluster (Jeffries et al. 2003) reveals several stars with intermediate levels of lithium contemporaneous with the dominant population of lithium-depleted stars. Different theoretical models of M0 stellar interiors give very different predictions of lithium depletion in the 10 – 20 Myr age range (see Figure 9 in Jeffries et al.). Detailed modeling of solar mass PMS stars shows that slow or rapid lithium depletion in 10 – 20 Myr can readily be explained by small changes in convection zone properties (Piau & Turck-Chièze 2002). It is thus reasonable to conclude that GJ 3305 is an OSCA member that experienced rapid depletion of lithium.

51 Eri and GJ 3305 lack significant  $K$ -band excesses and thus lack massive inner protoplanetary disks. Stars devoid of inner disks at  $t \simeq 10$  Myr are known in other OSCA outlying groups, e.g. in the TWA (Uchida et al. 2004) and the  $\eta$  Cha cluster (Lyo et al. 2003), and have been inferred from the wide range of rotation rates measured in the Pleiades

and other ZAMS clusters. Such stars are excellent candidates for searches for outer disks at mid-infrared wavelengths using the *Spitzer Space Telescope*, and high spatial resolution surveys for Jovian-mass protoplanets.

Kinematical evidence indicates the binary system is an outlier of the OSCA, similar to members of the BPMG, TWA,  $\eta$  Cha cluster, and others shown in Figure 1. The 51 Eri system is the most distant member yet found, lying  $100^\circ$  in the sky and 110 pc in space from the rich LCC OSCA subgroup with age  $\sim 17$  Myr (Mamajek et al. 2002). This can happen if the molecular cloudlet from which the 51 Eri system was formed was imparted a velocity of  $\sim 9 \text{ km s}^{-1}$  with respect to the more massive molecular cloud that formed the LCC subgroup. Such velocity differences are commonly seen in giant molecular cloud complexes that give rise to OB associations and can be imparted to disperse young stellar systems (Feigelson 1996). Yet, the relative velocity of the 51 Eri and GJ 3305 components could not have remained bound if they experienced a relative motion greater than  $1 \text{ km s}^{-1}$ . The HD 104237 quintet (Feigelson et al. 2003) and the HD 172555/CD  $-64^\circ 1208$  binary are similarly dynamically fragile multiple systems among OSCA outliers.

The 51 Eri/GJ 3305 binary system is thus a valuable tool in several respects. It validates the use of kinematic extrapolations of motions across the sky to find OSCA outliers. It supports arguments for distributed star formation in turbulent giant molecular cloud complexes producing small stellar groups which disperse far from the rich OB associations. GJ 3305 can be studied as an example of rapid lithium depletion in PMS stars. Finally, as one of the closest stellar systems with an age comparable to the later phases of planet formation, both 51 Eri and GJ 3305 represent excellent laboratories for the search for older protoplanetary disks or recently formed protoplanets.

This work was supported by NASA contract AR5-6001X (Garmire, PI). WAL acknowledges support from a UNSW@ADFA Special Research Grant. We thank L. W. Ramsey (Penn State) for rapid access to the Hobby-Eberly Telescope, L. A. Crause (SAAO), Charles Poteet (WKU), John Cybulski and Ethan Jordan (Penn State) for assistance. The referee, Alex Brown (Colorado) provided very helpful commentary. The effort benefited from on-line data resources from the Centre des Données Stellaires (Strasbourg), Astrophysics Data System (Smithsonian Astrophysical Obs.), High Energy Astrophysics Science Archive Research Center (NASA-GSFC), and the Infrared Space Archive (NASA-IPAC).

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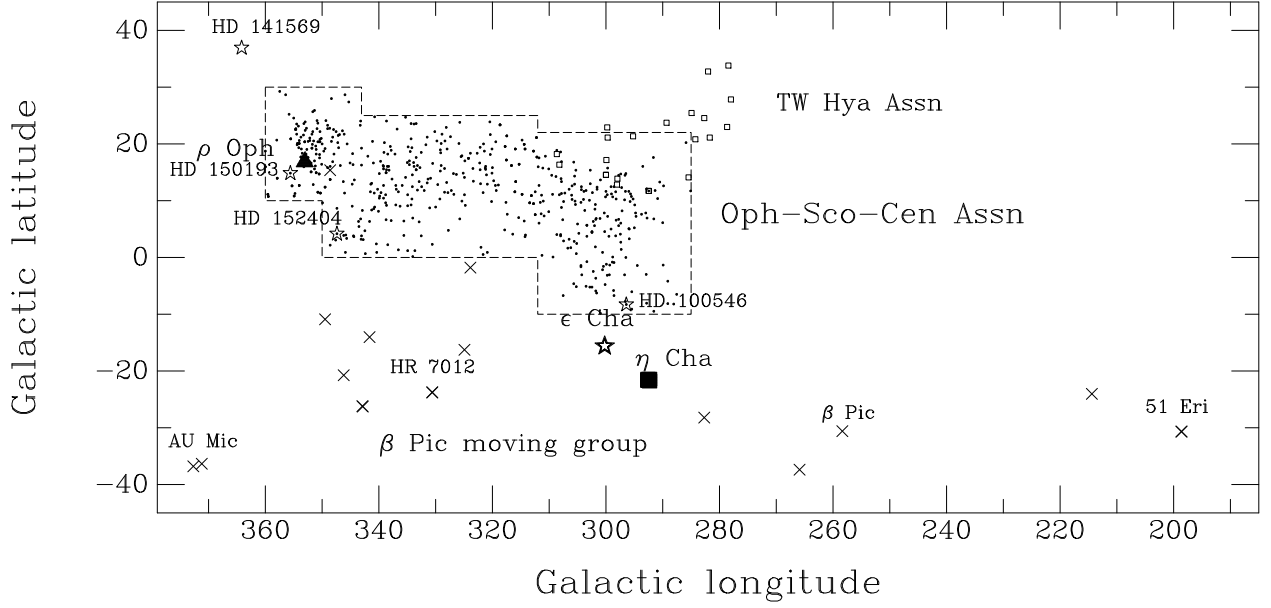


Fig. 1.— Diagram of  $\sim 1/3$  of the celestial sphere in Galactic coordinates showing nearby stars and PMS groups kinematically associated with the Oph-Sco-Cen Association (OSCA). References and further discussion are given in Feigelson et al. (2003).

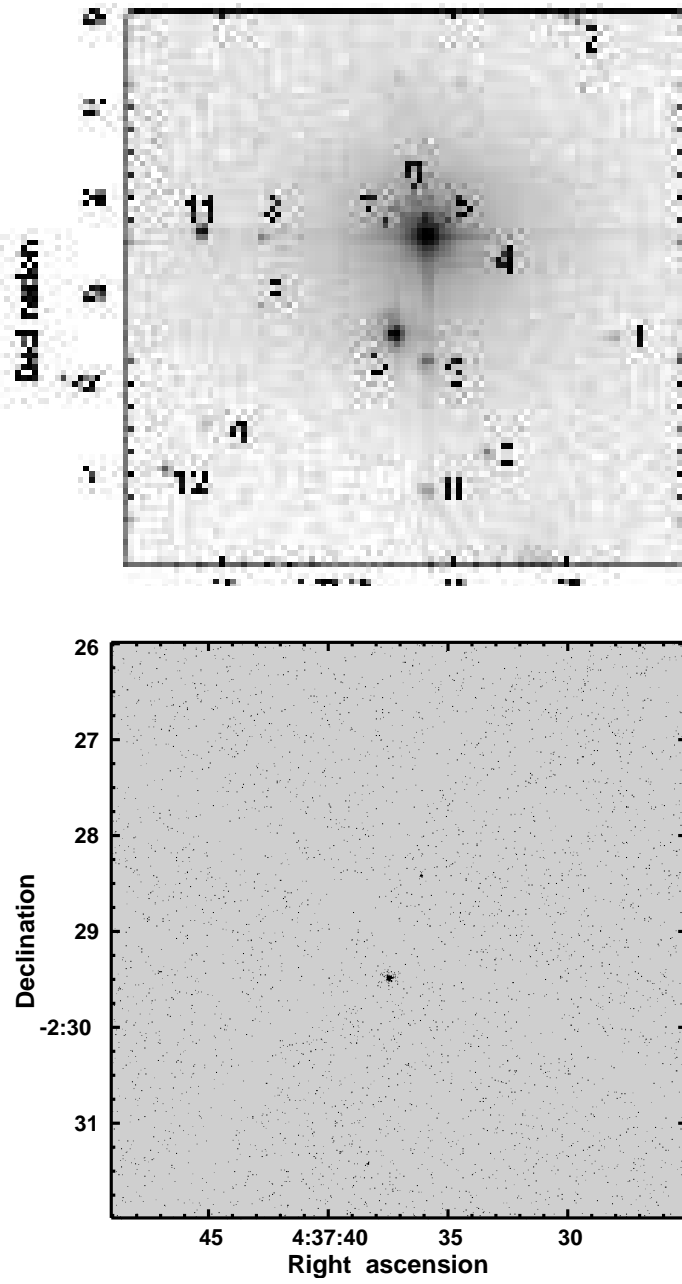


Fig. 2.— (Top) A  $6' \times 6'$  region around 51 Eri from the 2MASS  $J$ -band survey. The numbered stars are listed in Table 1, and ‘g’ refers to instrumental glint and ghost images. Star 5 is 51 Eri and star 6 is GJ 3305. (Bottom) The same region from the *Chandra* ACIS image showing 51 Eri (faint, slightly north of center) and GJ 3305 (bright, slightly south of center).

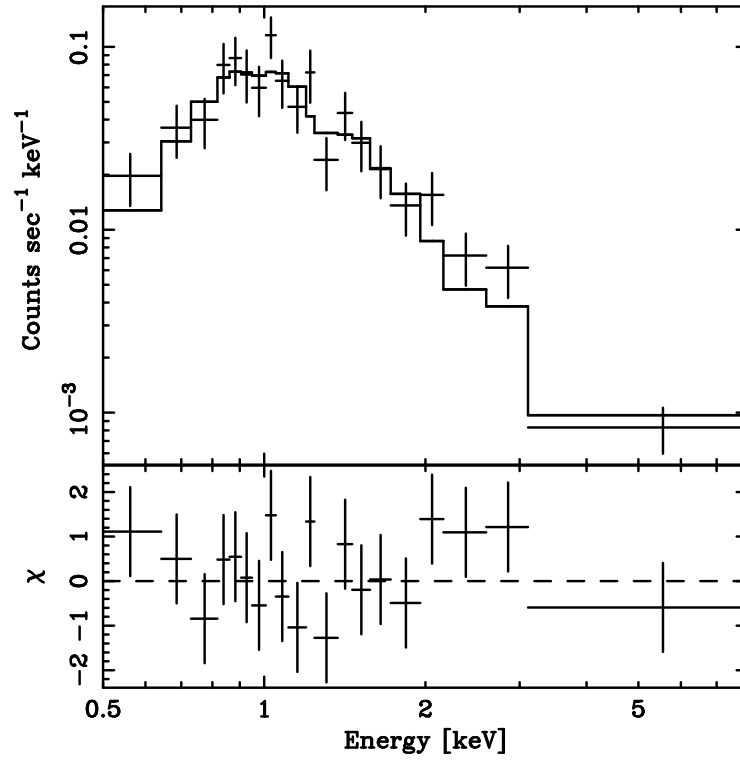


Fig. 3.— *Chandra* ACIS spectrum of GJ 3305.

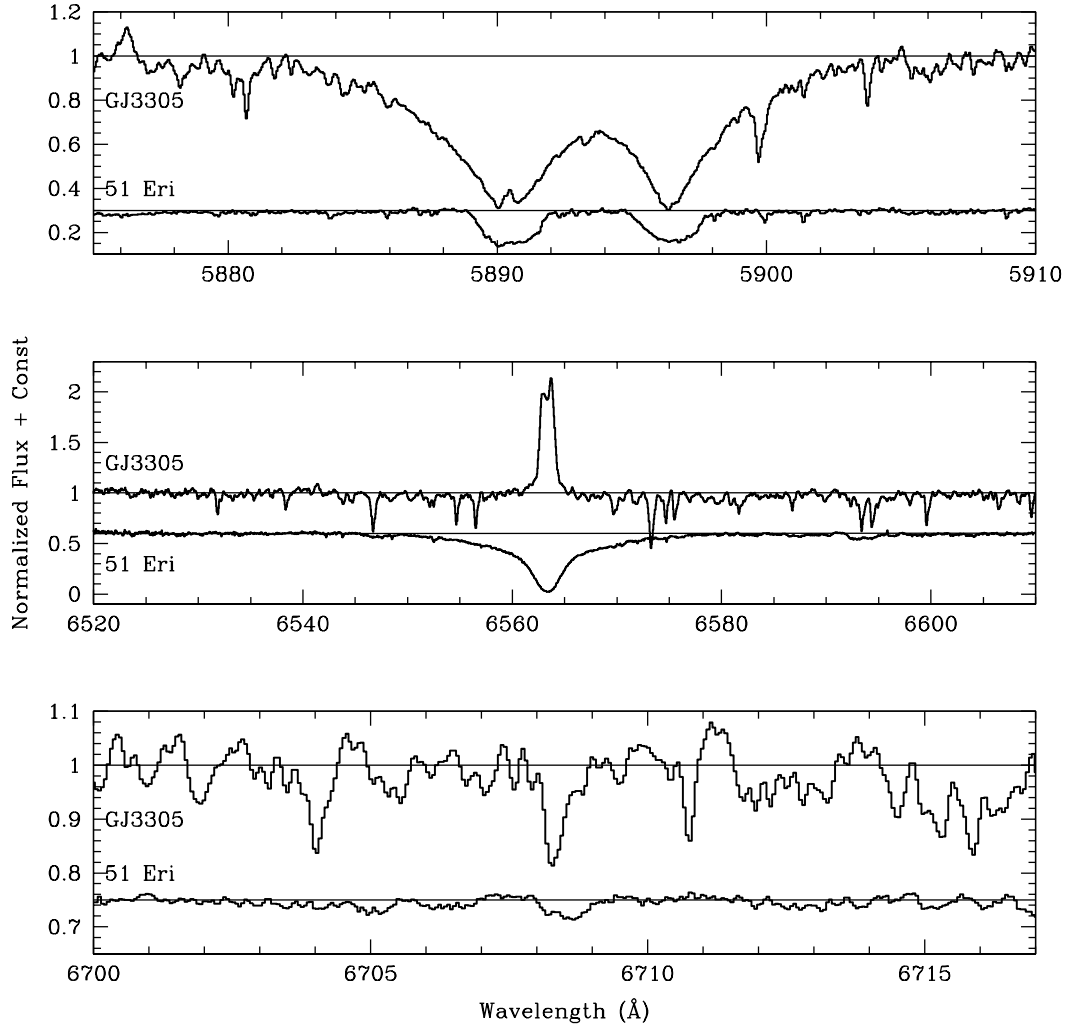


Fig. 4.— High-resolution echelle spectra from the Hobby-Eberly Telescope of 51 Eri and GJ 3305: (top) Na D region, (middle) H $\alpha$  region, and (bottom) Li 6708Å region. The 51 Eri spectra are offset from unity normalization for clarity.

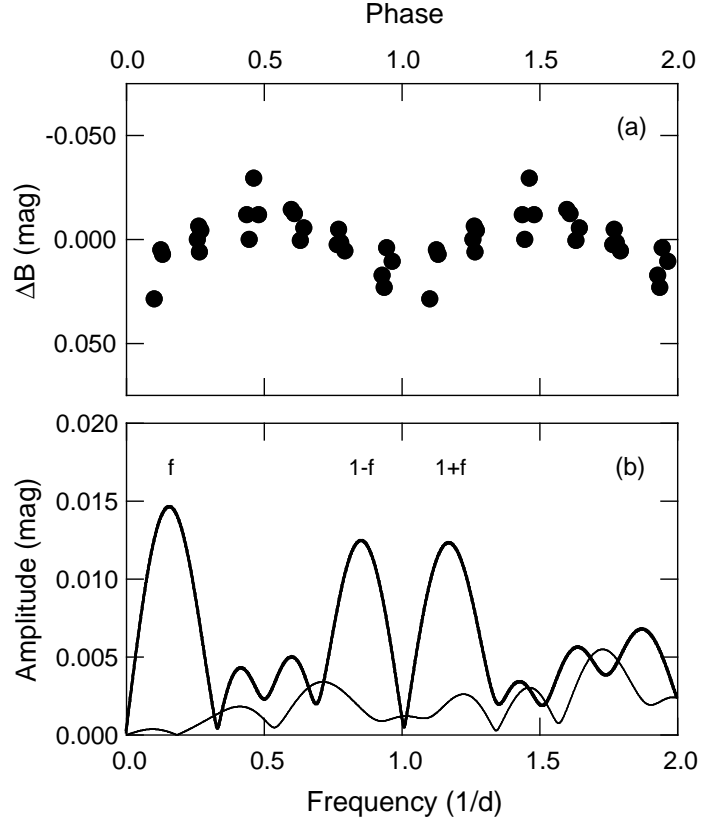


Fig. 5.— (Top) SAAO  $B$ -band observations of GJ 3305 phased to a periodicity of  $f = 0.164 \text{ d}^{-1}$  ( $P = 6.1$  days). (Bottom) Amplitude spectra of the original  $B$ -band dataset (upper bold line) and the pre-whitened dataset following removal of the  $f = 0.164 \text{ d}^{-1}$  periodicity (lower thin line). The  $\pm 1 \text{ d}^{-1}$  aliases of the periodicity resulting from observations being made at a single observing site are identified.

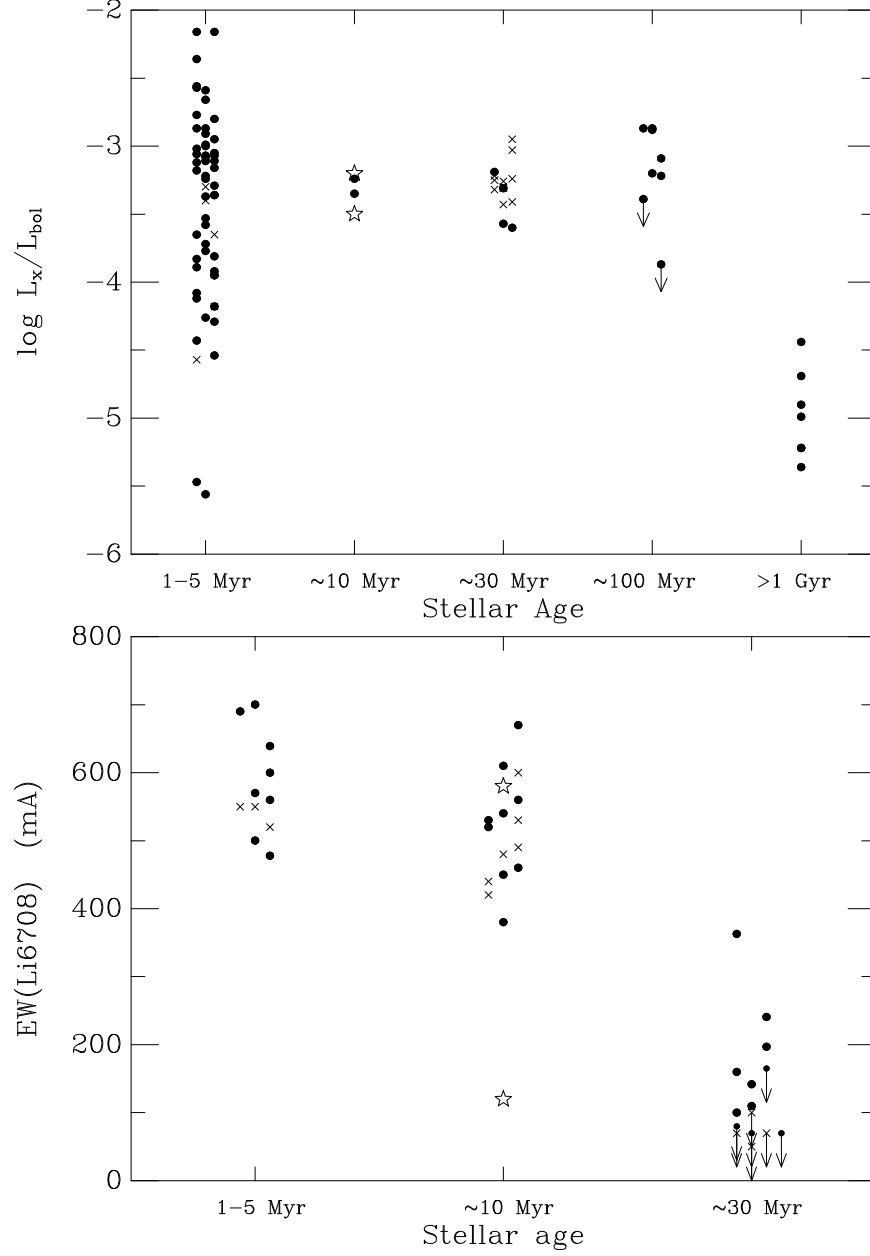


Fig. 6.— Distributions of (top) X-ray emissivity  $\log L_x/L_{bol}$  and (bottom) lithium 6708Å line equivalent width as a function of stellar age for stars with spectral types in the narrow range M0.0-M1.0. GJ 3305 and CD -64°1208 are shown as large open stars. Other symbols and details of the plotted values are given in footnote 3

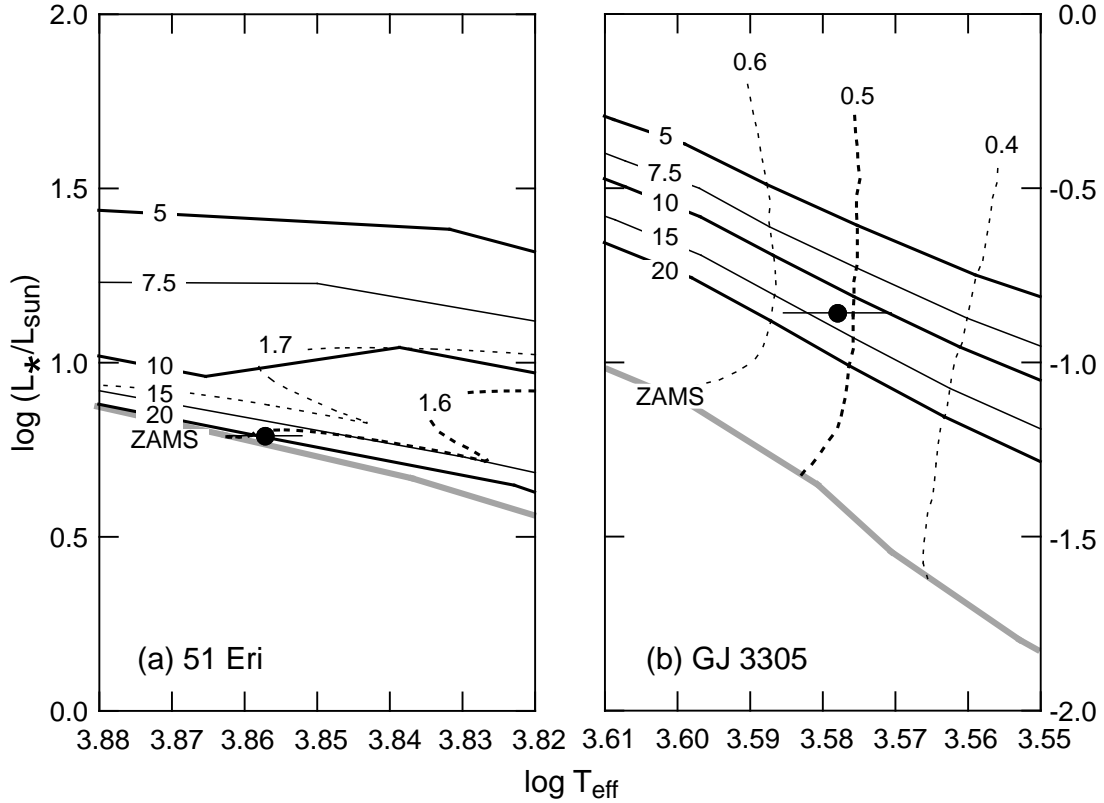


Fig. 7.— HR diagram location for (left) 51 Eri and (right) GJ 3305, compared to the PMS grid of Siess et al. (2000). Error bars for 51 Eri and GJ 3305 assume a nominal  $\pm 0.5$  sub-type in the spectral types for these stars of F0 and M0.5, respectively. Dwarf temperature and bolometric correction sequences have been assumed. Isochrones are in units of Myr; isomass lines in units of  $M_{\odot}$ . For GJ 3305, we adopt an age of  $13^{+4}_{-3}$  Myr.

Table 1. Stars in the vicinity of 51 Eri

#	R.A.	Dec.	UCAC #	Other catalogs	UC	$J$	$\mu_\alpha$	$\mu_\delta$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
1	28.0	29 31	30947507	CMC, USNO	15.0	13.5	12.3±7.5	-6.8±7.5
2	29.6	26 04	30947509	GSC	14.3	13.3	5.3±5.4	-10.6±5.4
3	33.5	30 36	30794265	CMC, USNO	14.1	13.1	5.6±7.6	-5.2±7.6
4	33.8	28 39	30947515	APM	15.5	14.6	7.4±7.5	-1.4±7.5
<b>5</b>	<b>36.1</b>	<b>28 25</b>	...	<b>51 Eri, SD, WDS, CCDM, ...</b>	<b>5.2</b>	<b>4.7</b>	<b>43.3±0.8</b>	<b>-64.3±0.6</b>
<b>6</b>	<b>37.5</b>	<b>29 28</b>	<b>30947521</b>	<b>CMC, GJ, StKM, RBS, ...</b>	<b>10.0</b>	<b>7.3</b>	<b>46.1±2.8</b>	<b>-64.8±3.0</b>
7	38.0	28 16	30947523	WDS, CCDM, HIC	11.8	11.3	0.6±1.4	20.2±1.4
8	43.3	28 25	30947531	CMC	14.2	13.3	12.9±7.5	-3.2±7.6
9	43.4	29 11	30947532	CMC	15.9	14.4	6.3±7.5	-2.8±7.5
10	45.6	30 26	30794283	...	14.6	13.6	-5.9±7.5	-9.5±7.5
11	45.9	28 22	30947535	CMC, GSC, SD, Tycho, ...	10.9	10.3	7.8±2.9	-6.0±3.3
12	47.4	30 57	30794286	...	13.1	12.1	-4.8±7.5	-8.7±7.5

Note. — Table columns: Col 1. Running star number from Figure 2a  
Col 2-3. Right ascension and declination, J2000  
Col 4. UCAC2 star number (Zacharias et al. 2003)  
Col 5. APM = Automated Plate Measurement catalog APMCAT-POSS1-1.0 (Irwin & McMahon 1992); CCDM = Catalogue of the Components of Double and Multiple Stars (Dommanget & Nys 2002); CMC = CMC12 (Version 1.0) catalog (Evans et al. 2002); GJ = Catalog of Nearby Stars, Preliminary 3rd version (Gliese & Jahreiss 1995); GSC2 = Guide Star Catalog (version 2.2) from the Palomar Schmidt telescope; RBS = ROSAT Bright Survey (Voges et al. 1999); SD = Southern Durchmusterung (Schonfeld 1886); StKM = (Stephenson 1986); Tycho = Tycho 2 catalogue (Høg et al. 2000); USNO = USNO-B1.0 catalog (Monet et al. 2003); WDS = Washington Visual Double Star Catalog (Worley & Douglass 1997)  
Col 6. UCAC magnitude (between  $V$  and  $R$  band,  $\pm 0.3''$  accuracy), except for 51 Eri ( $V$  magnitude)  
Col 7.  $J$  band magnitude from 2MASS All-Sky Point Source Catalog Col 8-9. Proper motion from UCAC2 (Zacharias et al. 2003), except for 51 Eri from *Hipparcos*.

Table 2. X-ray properties of 51 Eri and GJ 3305

Property	51 Eri	GJ 3305
CXOU	043736.12-022824.7	043737.46-022928.3
RA	04 <sup>h</sup> 37 <sup>m</sup> 36.12 <sup>s</sup>	04 <sup>h</sup> 37 <sup>m</sup> 37.46 <sup>s</sup>
Dec	−02° 28′24.7″	−02° 29′28.3″
Extr counts	41	222
Soft counts	41	182
kT	0.2	0.6 and 2.8
Flux	$1.3 \times 10^{-13}$	$1.6 \times 10^{-12}$
Luminosity	$1.4 \times 10^{28}$	$1.7 \times 10^{29}$